

High Energy Radiation from Black Holes: A Summary

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Bright γ -ray flares observed from sources far beyond our Galaxy are best explained if enormous amounts of energy are liberated by black holes. The highest-energy particles in nature—the ultra-high energy cosmic rays—cannot be confined by the Milky Way’s magnetic field, and must originate from sources outside our Galaxy. Here we summarize the themes of our book, “High Energy Radiation from Black Holes: Gamma Rays, Cosmic Rays, and Neutrinos,” just published by Princeton University Press. In this book, we develop a mathematical framework that can be used to help establish the nature of γ -ray sources, to evaluate evidence for cosmic-ray acceleration in blazars, GRBs and microquasars, to decide whether black holes accelerate the ultra-high energy cosmic rays, and to determine whether the Blandford-Znajek mechanism for energy extraction from rotating black holes can explain the differences between γ -ray blazars and radio-quiet AGNs.

I. SCIENTIFIC HYPOTHESES

In our book [1], a mathematical formulation of high-energy radiation processes and strong-field gravity is presented. This framework provides a starting point to investigate the following hypotheses:

1. The most energetic and powerful radiations are made by processes taking place in black-hole jets.
2. Ultra-high energy cosmic rays (UHECRs) are accelerated by radio and γ -ray loud blazars and GRBs.
3. Turbulence and shocks accelerate particles to high energies through Fermi processes.
4. The energy source of black holes with relativistic jets is black-hole rotation.

II. ESTABLISHING THE HYPOTHESES

We do not attempt to present a comprehensive summary of the observational background to be tested in our book, which is impossible given the rapidly expanding empirical data base arising from multiple facilities, in particular, the Fermi Gamma ray Space Telescope, the MAGIC, HESS, and VERITAS ground-based γ -ray telescopes, the Pierre Auger Cosmic Ray Observatory, and the IceCube Neutrino Observatory. Instead we present a mathematical formalism to help researchers establish or refute the hypotheses listed above. Here we mention some observations that drive the study, and related subjects dealt with in the book.

A. Black-Hole Jets as Sources of Energetic Radiations

The Fermi telescope, building on the success of the Energetic Gamma Ray Experiment Telescope (EGRET) on the Compton Gamma Ray Observatory, found that ~ 100 MeV – GeV γ rays are produced by the blazar AGN class. More than 30 blazar AGNs, principally of the X-ray selected BL Lac class, have now been detected with ground-based γ -ray telescopes. At least 12 GRBs of both the long soft and short hard class have been detected with the Large Area Telescope (LAT) on Fermi. Before that, five spark chamber events and several TASC (Total Absorption Shower Counter)/BATSE (Burst and Transient Source Experiment) events on CGRO, showed that GRBs produce extremely luminous multi-MeV/GeV emissions. Galactic microquasars like LS 5039 and Cyg X-1 are also found to be γ -ray sources. Powerful extragalactic γ -ray sources are thought to be formed by black-hole jets, with the jets nearly aligned to the observer.

To establish whether black-hole jets are the sources of luminous γ radiations, we develop the theory of relativistic flows, starting with relativistic kinematics and special relativity. Compton and synchrotron processes are treated with the goal of presenting a framework from which to model the multiwavelength spectral energy distributions of high-energy radiation sources. Starting from the Compton cross section, relations are derived to model external Compton scattering involving surrounding isotropic radiation fields and anisotropic accretion disk radiation fields. The formalism applies to scattering throughout the Thomson and Klein-Nishina regime, though δ -function approximations are provided to make simple back-of-the-envelope estimates.

Synchrotron radiation formulae are presented, and the synchrotron self-Compton and synchrotron self-

absorption processes are developed. The $\gamma\gamma$ pair production process, starting from the elementary $\gamma\gamma$ cross section, is applied to γ -ray attenuation by target photons found in sources of high-energy radiation, and by target photons of the extragalactic background light.

With this formalism in hand, the nature of high-energy radiation sources can be examined. This includes tests for relativistic beaming such as the Compton catastrophe, whereby the size scale of the source determined directly from radio observations or indirectly from the variability timescale of the radiation implies the level of the Compton-scattered X-ray and γ -ray flux if the radio-through-optical/UV emission is nonthermal synchrotron radiation. Minimum bulk Lorentz factors of relativistic outflows from $\gamma\gamma$ opacity arguments are derived. Moreover, minimum power requirements for synchrotron sources can be determined from equipartition arguments. Together, these arguments point toward relativistic outflows from highly compact sources, which almost certainly implicate black holes as the engines of the luminous radiation.

B. UHECRs from Blazars and GRBs

Not even the highest energy cosmic rays point back to their sources due to deflections by the Galactic and intergalactic magnetic fields, which has made the birth of charged-particle astronomy difficult. In the meantime, the sources of the UHECRs can be established indirectly by identifying γ -ray signatures of hadronic acceleration, and directly by detecting neutrinos from their sources with, for example, the IceCube neutrino telescope. Discriminating leptonic from hadronic emission signatures in the absence of neutrino detection represents an important challenge in the Fermi era. Identification of features peculiar to hadronic processes, such as orphan flares in blazars, represents one approach, and the interpretation of unusual temporal and spectral behaviors as indicated in delayed onset or extended radiation from GRBs, represents another.

A treatment of photohadronic processes is given. This includes photomeson production from proton-photon interactions, ion-photon photopair (Bethe-Heitler) processes, and ion photodisintegration. To illustrate the use of the photohadronic physics presented in the book, a calculation is made of the UHECR spectrum from the superposition of long-duration GRB sources whose rate density is assumed to follow various star-formation rate functions. (This calculation is far more difficult if UHECRs are accelerated by blazars, insofar as supermassive black holes increase in mass with time, their fueling is episodic, and they come from various classes of objects, for example, BL Lac objects and flat spectrum radio quasars.) The associated GZK neutrino spectrum is calculated for an assumed long-duration GRB origin of the UHECRs.

The calculations are specific to UHECR protons, but photodisintegration cross sections and approximations are also presented, including giant dipole resonance and nonresonant channels. Calculations of neutrino production from nuclear photodisintegration is briefly described.

For completeness, binary collision processes useful for calculating radiation signatures from cosmic-ray interactions are given, including the processes of secondary nuclear production, bremsstrahlung, electron-positron annihilation, and Coulomb thermalization and knock-on electron processes.

C. Particle Acceleration in Black-Hole Jets

One of the important questions in high-energy astrophysics is the method by which cosmic rays are accelerated to \approx PeV energies by Galactic sources, and to ultra-high energies in extragalactic sources. The empirical data base that must be explained is extensive. This includes cosmic-ray anisotropy, ionic composition, and UHECR arrival directions. Features in the cosmic-ray spectrum include the knee at ≈ 3 PeV, the second knee at $\approx 4 \times 10^{17}$ eV, the ankle at $\approx 5 \times 10^{18}$ eV, and the cutoff at $\approx 6 \times 10^{19}$ eV, probably due to GZK effects.

A complete understanding of cosmic-ray origin requires that a mechanism for particle acceleration be identified. For this purpose, an introduction to Fermi acceleration is given, starting from the two distinct types of Fermi acceleration mechanisms due to shock acceleration resulting from particle diffusion across a shock front and convection downstream of the shock, and stochastic acceleration by plasma wave turbulence. Dimensional arguments leading to the Kraichnan and Kolmogorov wave turbulence spectra are given. The Hillas criterion, whereby allowed sites for particle acceleration to energy E are restricted to those which satisfy the condition that the Larmor radius is smaller than the size scale of the system, is presented.

First-order and second-order Fermi acceleration mechanisms are developed to the point where maximum particle energies in different astrophysical environments can be derived. These maximum particle energies then implicate different classes of sources as plausible sites for cosmic-ray acceleration. Acceleration of cosmic rays by supernova remnant shocks remains the favored explanation for the sources which accelerate galactic cosmic rays, and may very well be demonstrated through Fermi measurements of the γ -ray spectra of supernova remnants. UHECR acceleration in the shocks and turbulent plasma formed in the relativistic jetted outflows of black-hole jets is the most likely explanation for their origin, compared to, for example, highly magnetized neutron stars or accretion or merger shocks in clusters of galaxies.

The blast-wave physics developed over the past two decades to explain the extraordinarily luminous radiation from GRBs is also presented, including spectral and temporal SEDs from external shocks and colliding shells, photospheric emission, and neutron decoupling in the expanding fireball.

D. Energy Extraction through Blandford-Znajek Processes

If jetted black holes make the most energetic radiations in nature, with particle acceleration occurring via Fermi processes, a remaining question of fundamental importance is the energy source for these radiations. Accretion onto supermassive black holes obviously powers the luminous quasi-thermal emissions in active galaxies, but less obvious are the reasons for the differences between radio-quiet and radio-loud AGNs, or for the different classes of GRBs, including X-ray flashes, low-luminosity GRBs, and long duration GRBs.

We consider whether these differences may be due to the spin of the black hole, with the energy extracted through the Blandford-Znajek process. A treatment of general relativity and black-hole electrodynamics is given based on a “3+1” formalism that provides a more compact approach than found in the original treatment. On this basis, we have recast the constraint equation for a force-free black-hole magneto-

sphere in a form that allows one to search for analytic solutions. We derive an exact solution which does not give energy extraction, and an approximation solution which generalizes the Blandford-Znajek split monopole solution to arbitrary values of the black-hole spin parameter. This solution is considered in light of evidence for jetted outflows from black-hole sources.

III. SUMMARY

The science covered in our book and, in particular, the hypotheses outlined in the first section, will be addressed by the ongoing observational activity in high-energy astronomy. The hypothesis that the highest energy and most luminous radiations in nature, including the bright γ -ray flares from blazars and GRBs, and the UHECRs from unknown extragalactic sources, are energized by the rotational energy of spinning black holes, can be tested with observatories now in operation. This assertion will be established or refuted as new data is collected and analyzed.

Acknowledgments

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[1] Dermer, C. D., & Menon, G. 2009, “High Energy Radiation from Black Holes: Gamma Rays, Cosmic Rays, and Neutrinos,” (Princeton University Press: Prince-

ton, NJ)